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Phase I efforts demonstrated relationships between dry bulb temperature and AVHRR data and between wet bulb temperature and the total precipitable water derivable from TOVS data available from NOAA satellites. Algorithms for these relationship were developed.

Phase II of the research was initiated in June 1987. Additional ground truth data were collected for further refinement of these algorithms. Data were collected in arid regions of the southwestern United States. Additional data for moist, vegetated areas will be collected in the summer of 1988. (Kyhn...)

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SATELLITE REMOTE SENSING OF THE WET BULB GLOBE TEMPERATURE HEAT STRESS INDEX[1]

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ABSTRACT

The Wet Bulb Globe Temperature (WBGT) is the basic parameter used by the U.S. Army to quantify heat stress. The index is computed as a weighted sum of dry bulb, wet bulb and black globe temperature measurements. During 1985, Gulf Weather Corporation received a Small Business Innovation Research (SBIR) Phase I contract from the U.S. Army Research Institute of Environmental Medicine to determine if the WBGT could be determined from information routinely available from U.S. weather satellites.

Phase I efforts demonstrated relationships between dry bulb temperature and AVHRR data and between wet bulb temperature and the total precipitable water derivable from TOVS data available from NOAA satellites. Algorithms for these relationships were developed.

Phase II of the research was initiated in June 1987. Additional ground truth data were collected for further refinement of these algorithms. Data were collected in arid and extremely arid regions of the southwestern United States. Additional data for moist, vegetated areas will be collected in the summer of 1988.

This paper presents progress to date on algorithm development and discusses the ground truth data collection efforts and the satellite data analysis procedures.

1. INTRODUCTION

The research described in this paper is being conducted by Gulf Weather Corporation under a Small Business Innovation Research (SBIR) project sponsored by the U.S. Army Research Institute of Environmental Medicine (USARIEM). The Phase I contract was awarded in 1985 and completed in July 1986. During Phase I, ground truth data were collected from three sites. One very moist, one temperate and one semi-arid area were selected to give a cross-section of climatological influences. USARIEM also provided ground truth data for several sites. The initial research under Phase I showed the existence of relationships between (1) dry bulb temperature and Advanced Very High Resolution Radiometer (AVHRR) data from channel 4 and (2) wet bulb temperature and the total precipitable water available from TIROS Operational Vertical Sounder (TOVS) data from the NOAA-N weather satellites.

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[1]The work described in this paper is being conducted under a Phase II SBIR contract for the U.S. Army Research Institute of Environmental Medicine.

Phase II of the research was awarded to Gulf Weather Corporation during February 1987. Initial efforts were to plan and organize an extensive ground truth data collection effort in the southwest desert region of the United States. Rationale for selection and the makeup of the ground truth data base are provided later in the paper. This paper provides the status of the research up to this time.

The NOAA polar-orbiting satellites were selected for use in the project because of the availability of 2 satellites providing a total of 4 passes per day for AVHRR and TOVS data. Additionally, the AVHRR provides a fine resolution of 1.1 km at the satellite's nadir.

AVHRR channels 1 and 2 provide albedo values (reflectivity) which can be used to indicate surface characteristics, e.g., vegetative cover. Channel 3 is useful in temperature measurements at night but is usually too noisy during daytime passes. Channels 4 and 5 are often used in measurements of sea surface temperatures.

The Wet Bulb Globe Temperature (WBGT) is one of several indices used to express heat stress potential resulting from environmental parameters. The WBGT is computed as a weighted sum of the dry bulb (DB), wet bulb (WB) and black globe (BG) temperatures.

$$WBGT = 0.1\ DB + 0.2\ BG + 0.7\ WB \qquad (1)$$

Although there may be some singular, empirical relationship between satellite-derived data and WBGT, it was felt that the more direct approach of developing individual algorithms relating each of the WBGT's components to data routinely available from weather satellites would be preferable. Initial findings during the Phase I research indicated that this approach is feasible. The other approach, however, will also be considered.

2. WBGT COMPONENT DETERMINATIONS

2.1 DRY BULB TEMPERATURE

The NOAA-N polar-orbiting satellites are equipped with spectral scanners with several "windows" in a range of wavelengths from the visible to the far infrared. Short wavelengths (visible) provide albedo information, i.e., reflectivity, and long wavelengths (infrared) provide data on thermally emitted radiation from the earth.

During the Phase I effort the following relationship between the skin brightness temperature (T4) obtained from channel 4, and the surface dry bulb temperature (DB) was established.

$$DB = 22.23 + 0.31\ T4 \qquad (2)$$

In Eq. 2 the temperatures are expressed in degrees Celsius. This equation with data obtained during the Phase I effort are presented in Fig. 1. Data from recent ground truth data collection efforts are being analyzed to refine this algorithm.

2.2 WET BULB TEMPERATURE

The NOAA-N satellites also carry a TOVS (TIROS Operational

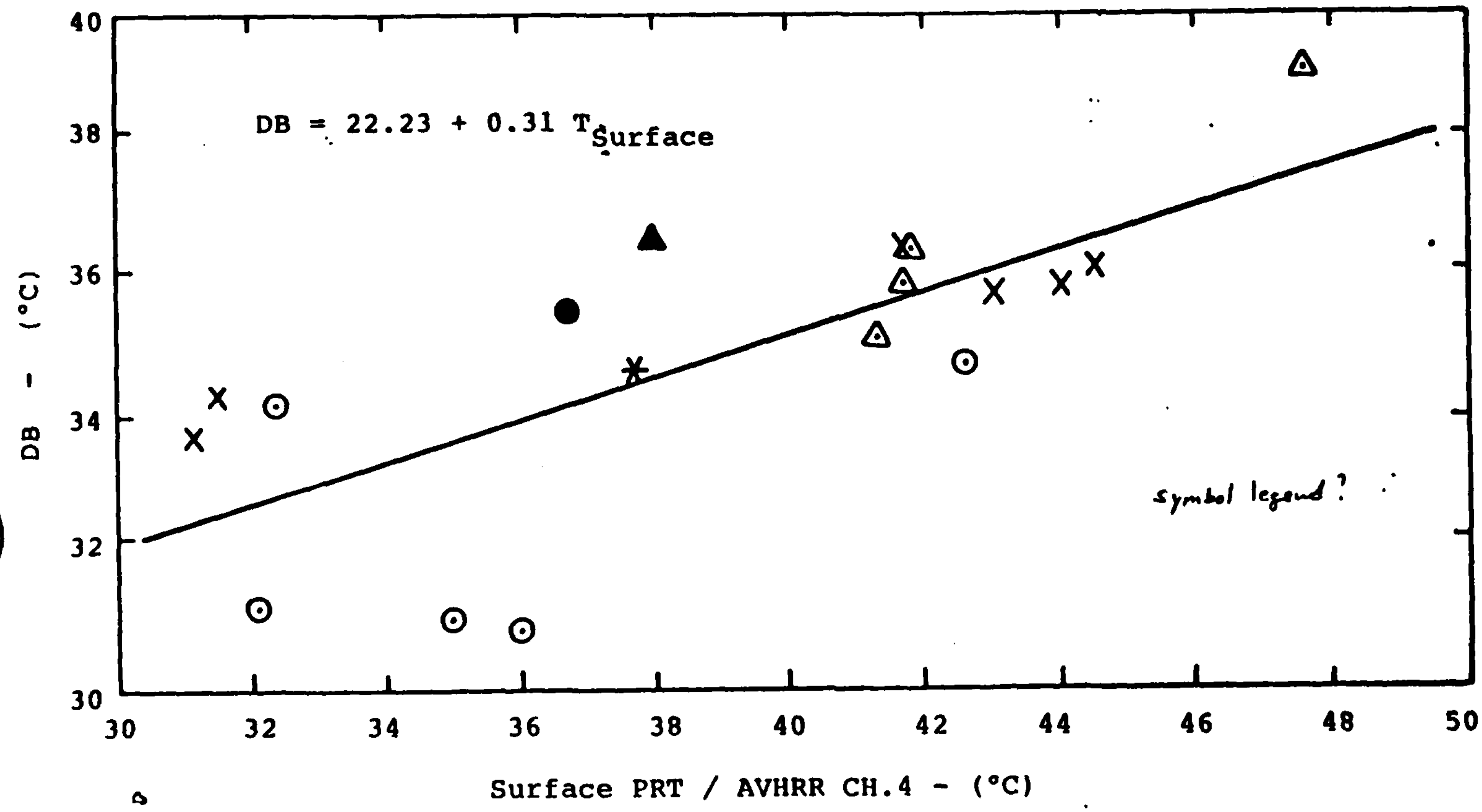

Figure 1. Relationship between dry bulb temperature and skin/surface temperature formulated during Phase I.

Vertical Sounder) package consisting of three instruments: a Microwave Sounding Unit (MSU), a Stratospheric Sounding Unit (SSU) and a High Resolution Infrared Radiation Sounder (HIRS/2). These instruments measure upwelling radiation at different spectral intervals. These data can be processed to provide earth-located estimates of atmospheric water vapor in three different levels. These values are usually expressed as depth of precipitable water. The sum of the values in all of the layers is an estimate of the total precipitable water (W).

In the Phase I data collection effort, radiosondes were launched to measure total precipitable water. A relationship between total precipitable water and surface wet bulb temperature, based on theoretical considerations (Phase I SBIR Report,1986), is expected to have the form

$$WB = a + b \ln(W) \tag{3}$$

in which W is expressed as the depth of condensed water in centimeters. A curve fit of the data yielded

$$WB = 5.29 + 15.97 \ln(W) \tag{4}$$

This relationship, developed during the Phase I effort, is presented in Fig. 2 with previous and newly acquired data. Although the previously developed relationship appears to maintain its validity, the data are being analyzed further because of an expected difference between daytime and nighttime.

A curve-fit with just the daytime values yields

$$WB = 8.17 + 12.6 \ln(W) \tag{5}$$

with a standard deviation of 1.7 C and $r^2 = 0.92$.

2.3 BLACK GLOBE TEMPERATURE

The Black Globe Temperature is the temperature measured by a black globe thermometer which consists of a thin copper sphere, painted matte black. A temperature sensing element is located at the sphere's center. This temperature depends on a number of variables including dry bulb temperature, wind speed, and mean radiant temperature.

While there may be some relationship between the black globe temperature and radiance and/or temperatures sensed by the AVHRR, a choice was made to use the model developed at USARIEM to predict the temperature (Matthew et al, 1986). The model takes as inputs: day of the year, time of day, geographic location, climate, dry bulb temperature and wind speed. The model has undergone some minor refinements and performs well for clear sky conditions.

A comparison of a typical time variation of the black globe temperature as predicted by the model together with field measurements is presented in Fig. 3 and is indicative of the performace of the model. It should be noted that the predicted black globe values were based on surface measurements of dry bulb temperature and wind speed.

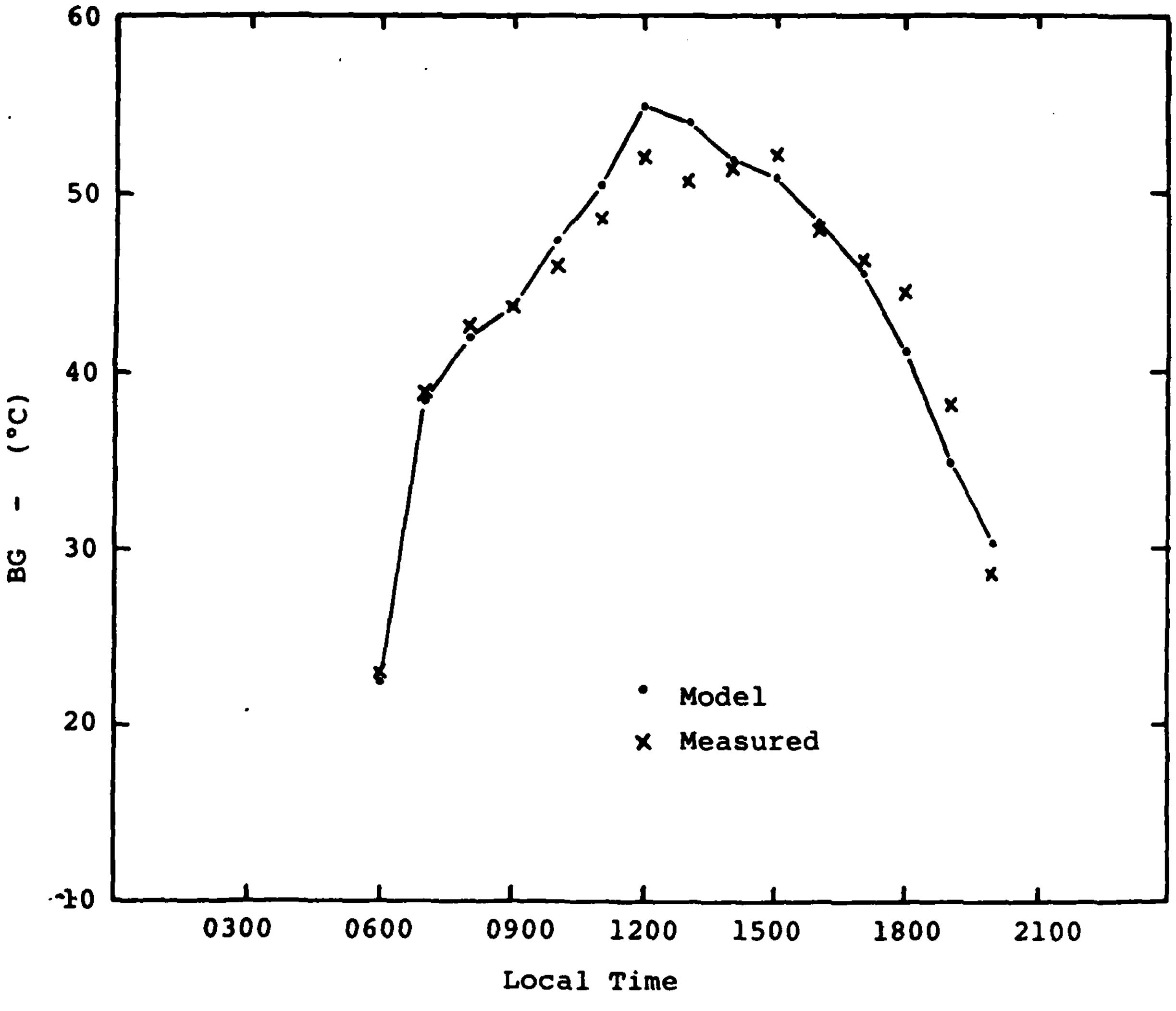

Figure 3. Typical variation of black globe temperature with temperatures predicted by the model.

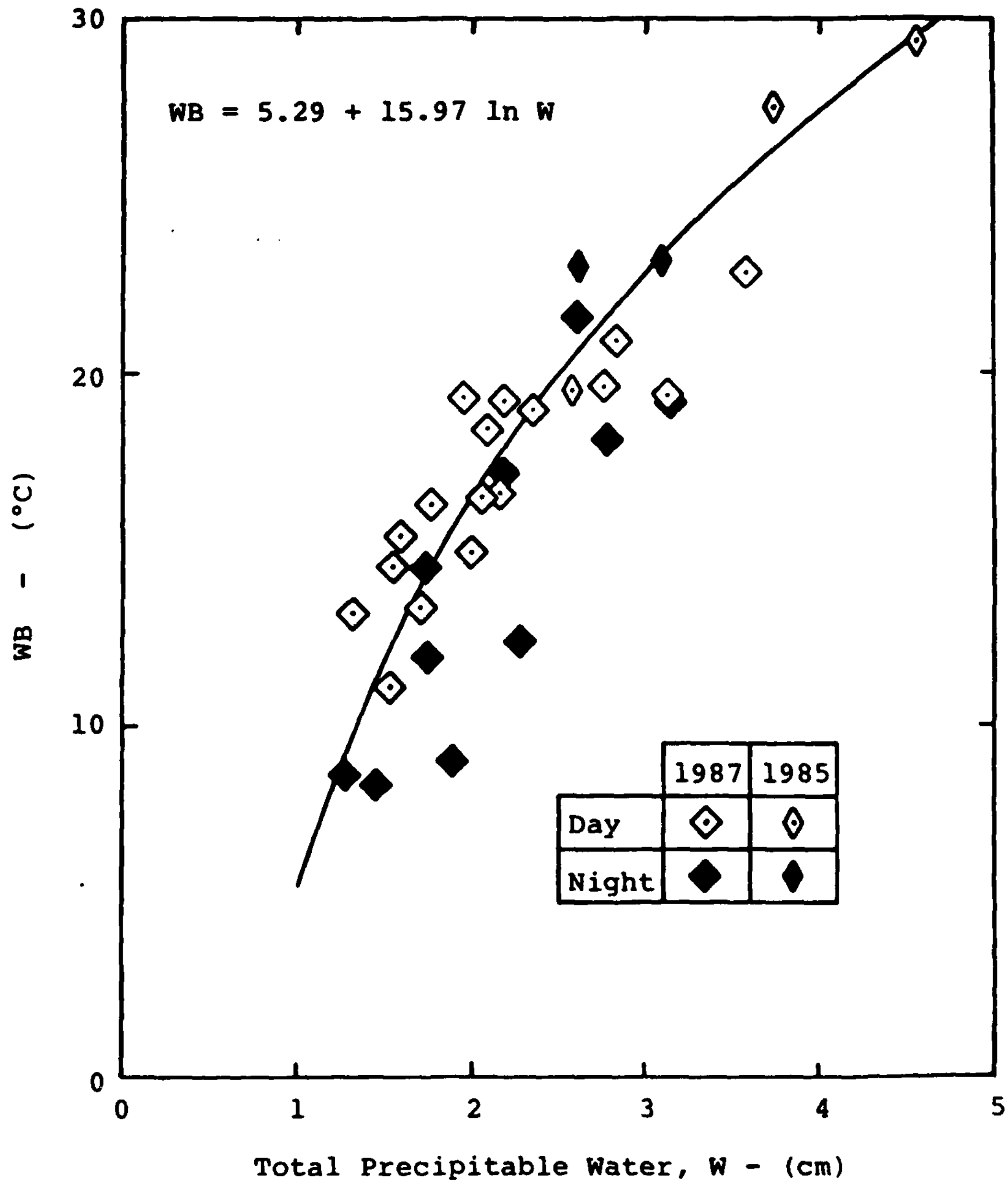

Figure 2. Relationship between wet bulb temperature and total precipitable water formulated during Phase I.

3. GROUND TRUTH DATA COLLECTION

During late June and early July of 1987 an extensive data collection effort was undertaken to acquire meteorological, earth, and satellite data at five selected sites in the arid Southwestern U.S., specifically in the Sonoran Desert. Of these sites, two were occupied for 24 hours and three were occupied for 48 hours.

3.1 SITE SELECTION

Field measurement sites were selected on the basis of geology and topography; the guiding concept being that the given terrain consists of areally extensive geologic "elements" which respond to diurnal heating and cooling cycles uniformly, but differently than the adjacent terrain element. These included alluvial fans, pediments carved on gensise, lava flows, sand dunes, dry sandy stream beds, granite domes, etc. For each site accurate latitude, longititude and elevation were determined from 7.5-minute topographic quadrangle maps.

The five sites with their latitudes and longitudes are given in Table 1.

Table I. Ground Truth Data Collection Sites, 1987

Site	Location	Latitude	Longitude
I	Tucson, AZ	32d 13.5m N	110d 46.0m W
II	Three Points, AZ	32d 0.3m N	111d 16.0m W
III	Gila Bend, AZ	33d 2.0m N	113d 3.0m W
IV	Yuma MCAS, AZ	32d 28.5m N	114d 23.5m W
V	Imperial Dunes, CA	32d 44.3m N	114d 53.0m W

3.2 FIELD MEASUREMENTS

Gulf Weather Corporation's meteorologists, at each observation site, recorded the following parameters on an hourly basis: dry bulb temperature, wet bulb temperature, black globe temperature, wind speed/direction, barometric pressure and cloud conditions. Three data recorders were also used to continuously record drybulb, black globe and shielded dry bulb temperatures at other locations within the satellite measurement area (pixel).

During each satellite overpass a high resolution radiosonde was launched from the main observation site to obtain an accurate profile of the vertical atmosphere. Additionally, during satellite overpass the following measurements were taken:

(a) soil surface temperature (within 1 cm of the soil surface)
(b) radiometric soil temperature using a hand-held precision radiation thermometer. At each site a series of 3 to 8 measurements were taken and recorded.
(c) solar altitude measurements using a clinometer
(d) soil samples were collected to be used for emissivity measurements.

3.3 SATELLITE DATA ACQUISITION AND PROCESSING

The NOAA satellite AVHRR data were acquired by the Scripps Satellite Oceanography Facility (SSOF, a UCSD-based satellite data receiving ground station). Data recovery was excellent with 36 satellite overpasses acquired synchronous with ground measurements and radiosonde launches. Of these only 2 passes were cloudy over the ground truth site.

The 2 operational NOAA satellites are NOAA-9 and NOAA-10. NOAA-9 is the 0300/1930 satellite and provides data for channels 1 through 5. NOAA-10 is the 0730/1930 satellite and provides no channel 5 data. During the 1500 overpass channel 3 radiation temperatures were found to be beyond the dynamic range of the sensor, i.e., unusable. Thus, the radiometric channels available from each pass are given in Table II.

TABLE II. NOAA-N AVHRR Data Availability

Local Time	Satellite	Channels
0300	NOAA-9	3,4,5 *
0730	NOAA-10	1,2,3,4
1500	NOAA-9	1,2,4,5
1930	NOAA-10	3,4 *

* insufficient illumination for channels 1 and 2

All of the satellite AVHRR data were captured and stored on computer compatible tape (CCT) for subsequent processing. These data were processed on the Hewlett Packard 3000 computer at SSOF using IDIMS software. Processing included subsectioning to isolate areas of interest to reduce computer processing time, calibration of data in the subareas (convert radiometric values to albedo or temperature), earth location (warp image to specific ground points of known location for accurate pixel location), and extraction of numerical values of albedo and temperature at ground truth sites.

4. CONTINUED EFFORTS

The Phase II research has been in progress for approximately one-fourth of the project's two year duration. A large quantity of data has been acquired. The analysis and evaluation of the data is underway with the expectation of refinements in the necessary algorithms.

Additional data collection efforts are planned for the summer of 1988 in more humid areas of the U.S.

The use of DMSP satellites to obtain higher resolution (25-km) precipitable water measurements is being considered.

ACKNOWLEDGEMENTS

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